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An X-ray Polarimeter for Constellation-X

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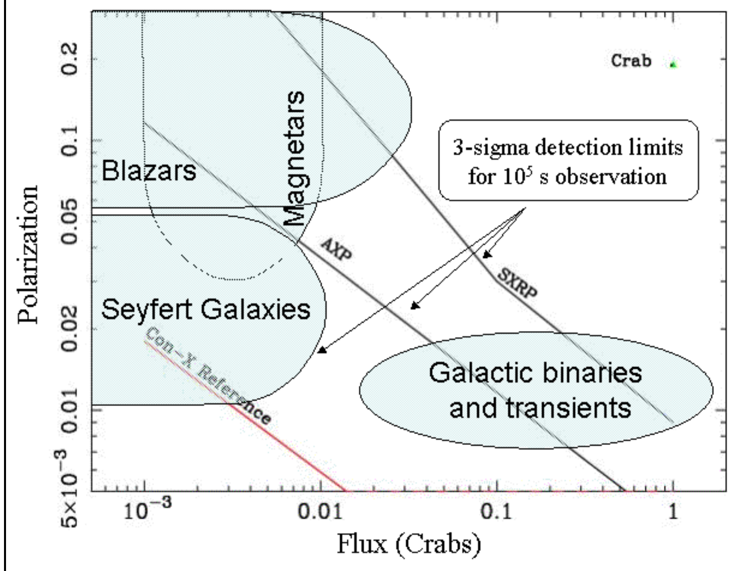
Astronomical X-ray Polarimetry

- Largely unexploited tool due to inadequate sensitivity of techniques based on Bragg and Thompson scattering in the 2-10 keV band

- Photoelectric polarimetry with gas pixel detectors greatly improves sensitivity

- We are also investigating a complementary photoelectric technique using Time Projection Chambers (TPCs) which provides even greater sensitivity via increased quantum efficiency.

- The proposed SEP consists of two polarimeters which can be commanded into (or out of) the optical path of two telescopes.



With gas pixel detectors, it is now possible to achieve greater sensitivity in a Small Explorer (AXP) than with a scattering polarimeter (SXRP) on a Hubble-sized mission. (Both are virtual missions)

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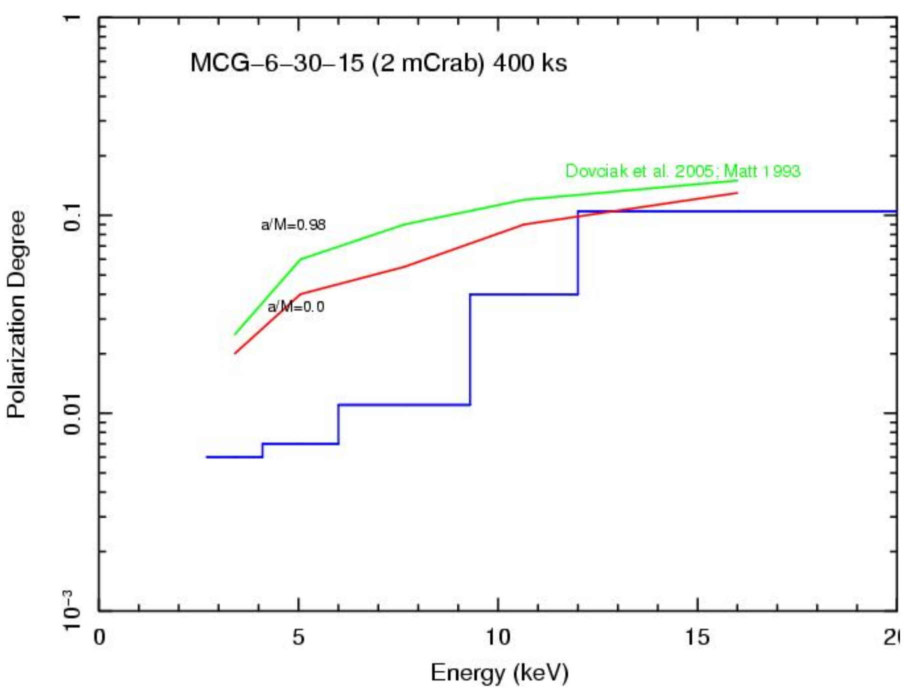
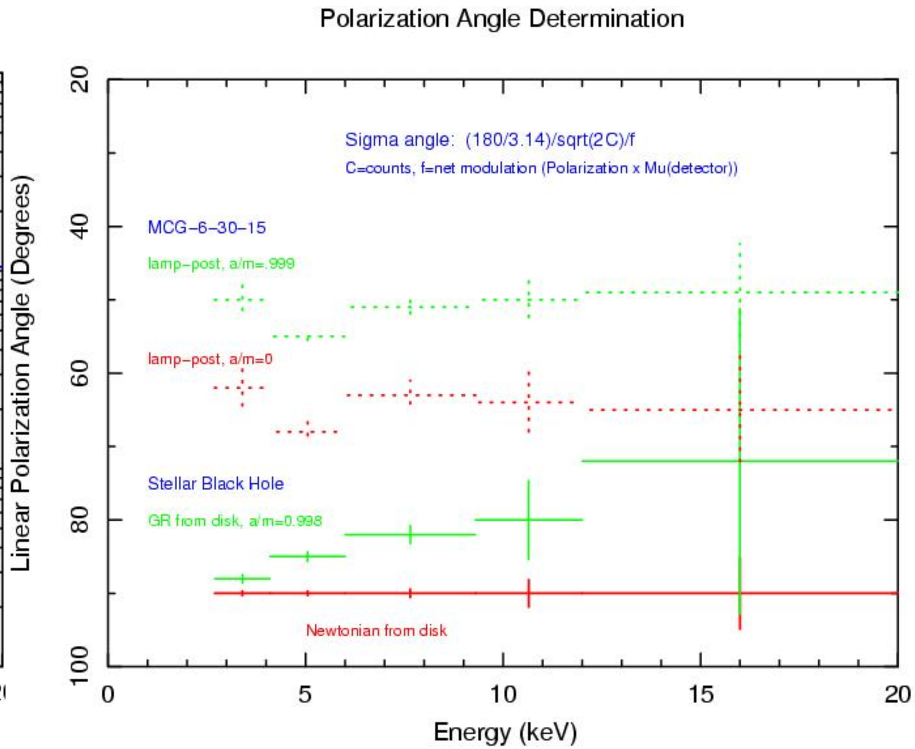
Scientific utility of polarization

- Black holes
  - Many effects, such as reflection off accretion disk or frame dragging, impart energy dependent polarization (degree and angle)





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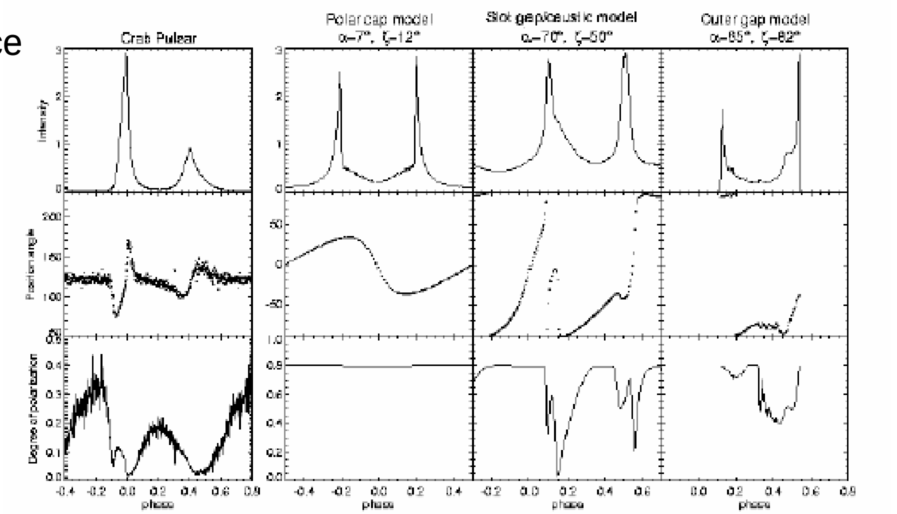
Scientific utility of polarization

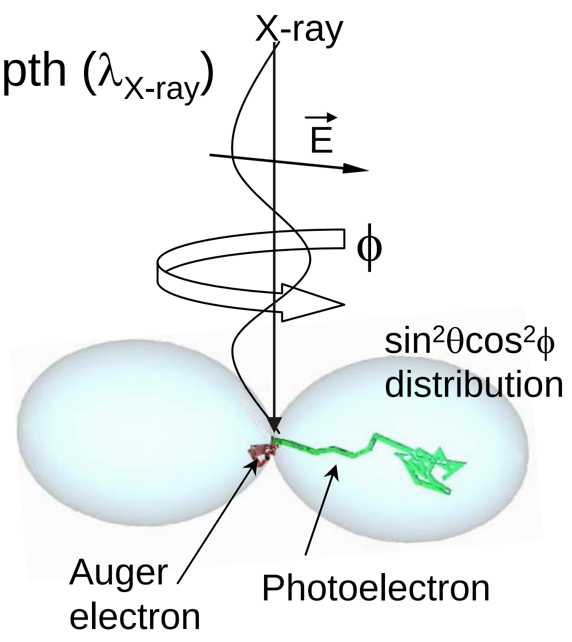
- Neutron Stars
  - Phase resolved polarization intensity and angle distinguish among models of Crab pulsar emission
  - Vacuum birefringence would induce energy dependent phase shifts
  - Average polarization is inversely proportional to fraction of surface observed. NS compactness is related to polarization

Optical - predictions for 3 X-ray emission models



Photoelectric X-ray Polarimetry

- Exploits: strong correlation between the X-ray electric field vector and the photoelectron emission direction
- Advantages: dominates interaction cross section below 100keV
- Challenge:
  - Photoelectron range < 1% X-ray absorption depth ($\lambda_{X\text{-ray}}$)
  - Photoelectron scattering mfp < e^- range
- Requirements:
  - Accurate emission direction measurement
  - Good quantum efficiency
- Ideal polarimeter: 2d imager with:
  - resolution elements $\sigma_{x,y}$ < e^- mfp
  - Active depth ~ $\lambda_{X\text{-ray}}$
  - => $\sigma_{x,y}$ < depth/10^3

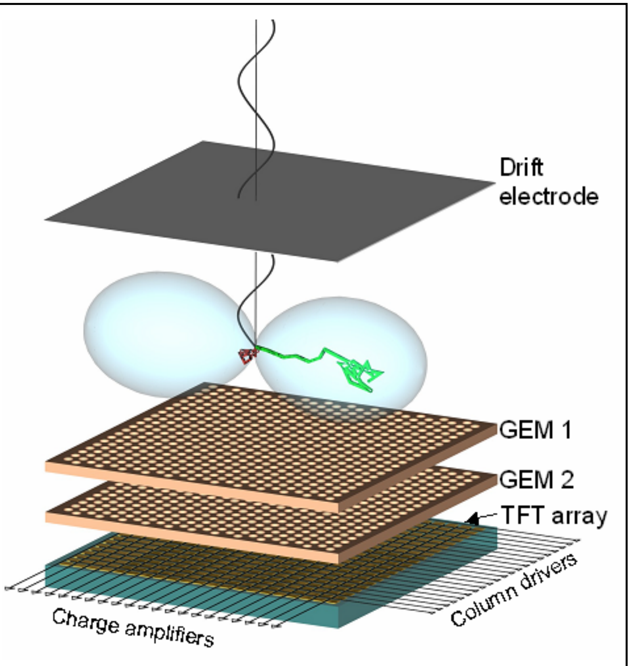


X-ray Polarimetry by Photoelectron Track Imaging

- First demonstrated in 1923 by C.T.R. Wilson in cloud chamber

- Modern track imaging polarimeters based on:
  1. Optical readout* of:
     - multistep avalanche chamber
     - GSPC
     - capillary plate proportional counter
  2. Direct readout# of GEM with pixel anode
     - resolution > depth/100
     - sensitive in 2-10 keV

- Active depth/$\sigma_{x,y}$ is limited by diffusion as primary ionization drifts through the active depth



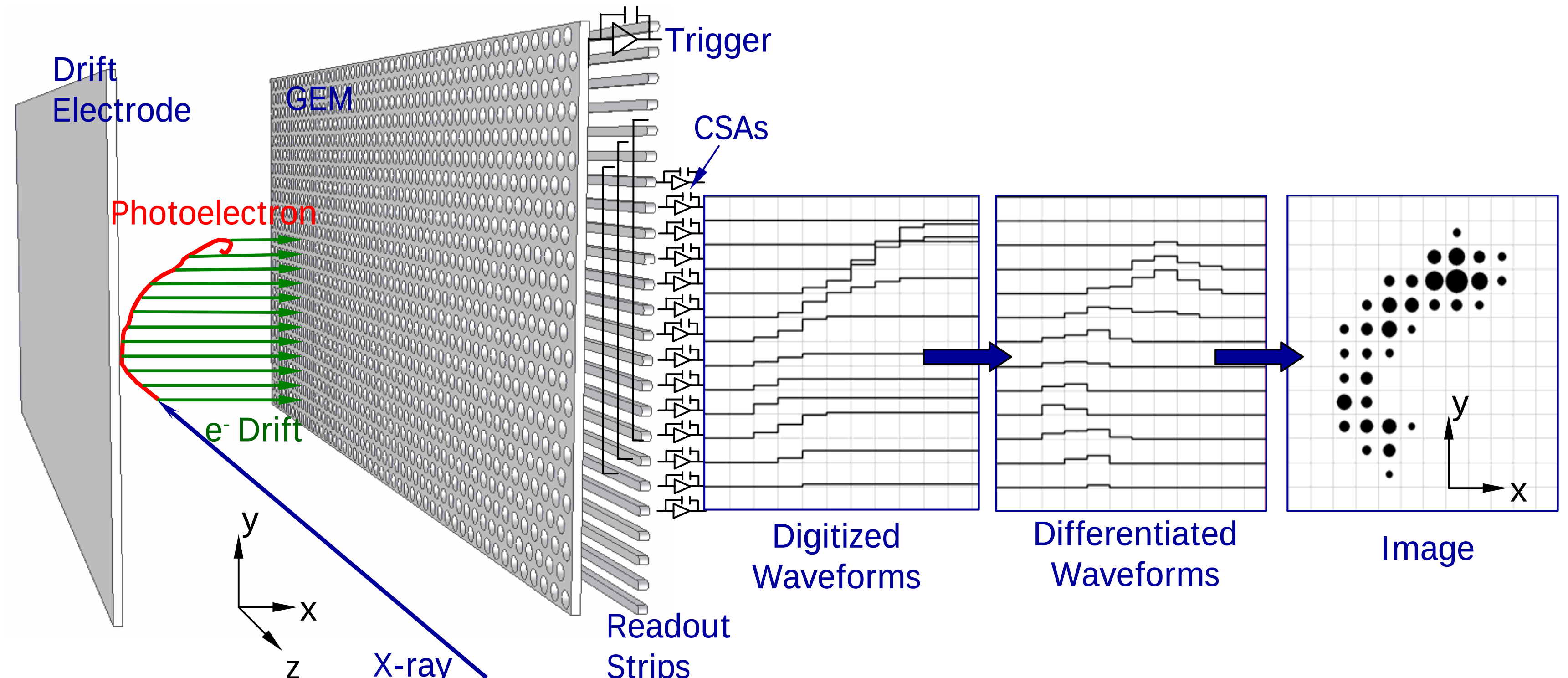
The geometry that affords the gas pixel polarimeter focal plane imaging limits its quantum efficiency

*Ramsey et al. 1992

#Bellazinni et al. 2003, 2006; Black et al. 2003

TPC Polarimeter Concept

- Drift direction is perpendicular to X-ray propagation so that diffusion is independent of the active depth
- Image in a plane normal to the detector elements using strip readout
- Pixels are formed by time projection, coordinates [arrival time,strip location]
- Drift height determined by collimation of beam



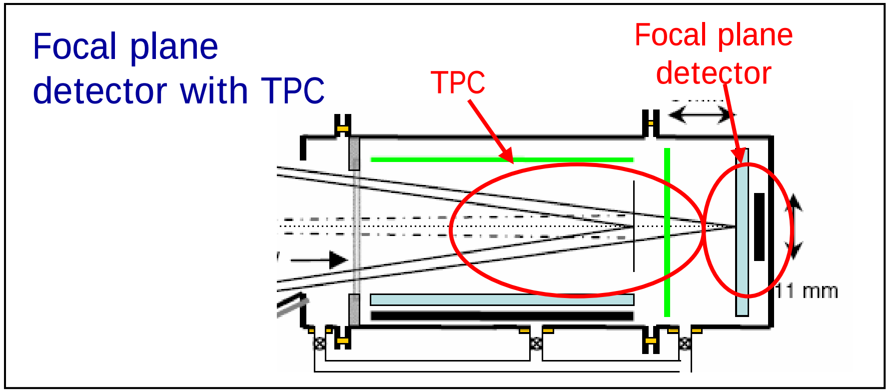
Tradeoffs in a TPC polarimeter

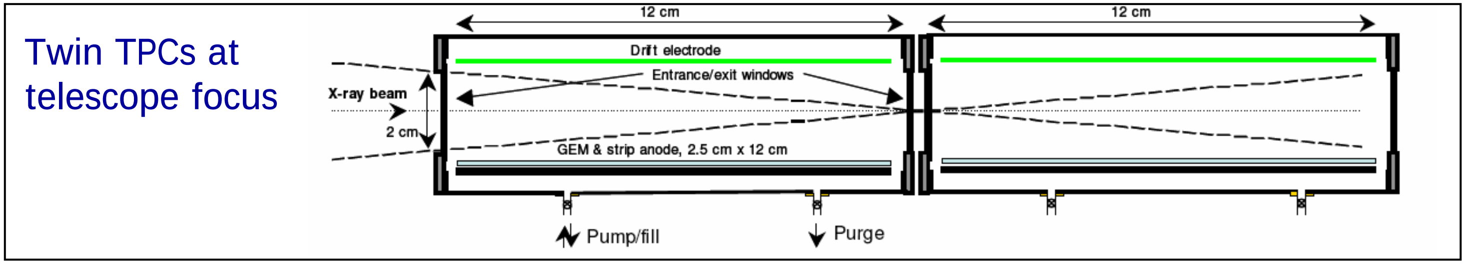
Pros

1. Improves quantum efficiency without loss of image resolution
2. Geometry enables multiple instrument concepts
3. Simplicity of construction

Cons

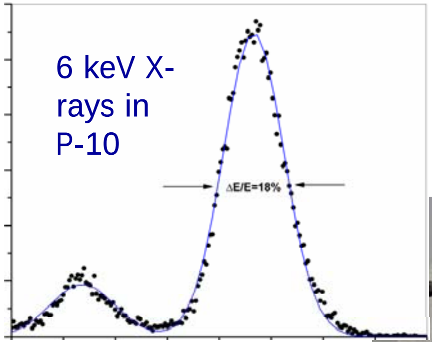
1. Rotationally asymmetric: requires careful control of systematics
2. Not focal plane imaging



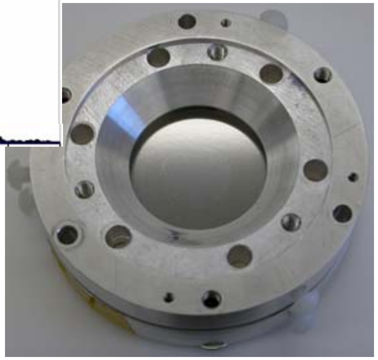


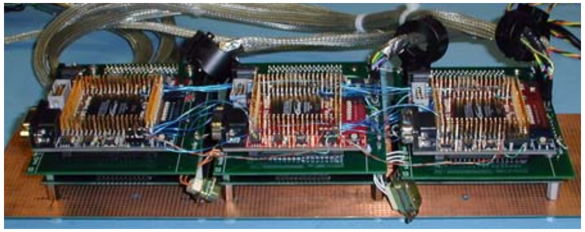
First prototype TPC polarimeter

- Made from off-the shelf components:
  - Pseudo-GEMs: etched stainless steel foils with spacer
  - Strip anode: standard printed circuit (130 micron pitch)
    - 96 strips, every 24th strip tied together (4 groups of 24)
    - 13mm(w) x 30mm(d) active area
  - Commercial charge-sensitive preamps
  - Homemade 24-channel, 50 MHz ADC using 8-channel TI chip

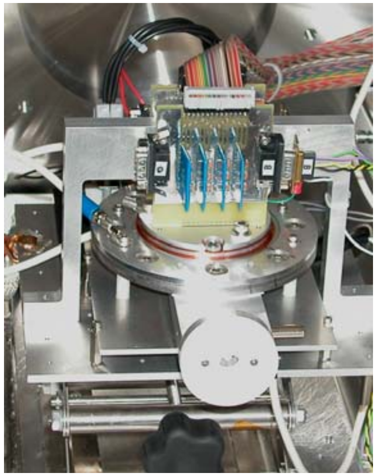


PGEM





24-channel waveform digitizer kludge based on 3 pixel ASIC readouts



Prototype polarimeter

TPC polarimeter measurements

- Measurements with:
  - polarized 6.4 keV X-rays at 0, 45, 90 degrees wrt drift direction
  - unpolarized 5.9 keV X-rays (Fe^{55}) before and after polarized
- In 18 mm-atm Ne:DME (50:50), 3 cm active depth, 460 Torr
- Drift velocity: one time bin (40 nsec) = strip pitch (130 microns)
- Use unpolarized X-rays to calibrate drift velocity by equalizing response at 0 and 90 degrees
- Gain = 3000, rms noise = $1000e^-$, pixel threshold = $2500e^-$

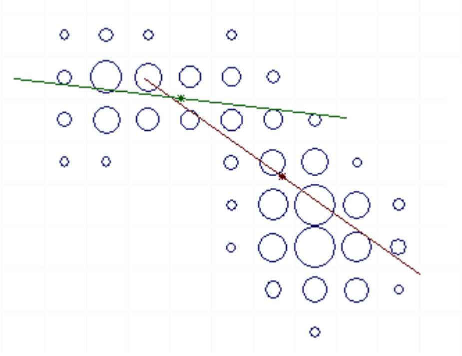
Emission Angle Estimation

- A two-stage, moments-based reconstruction
  - simplified “Pisa reconstruction” after Bellazzini et al
- First stage: estimate angle of emission as that of major axis of second moment-of-charge (M) about the barycenter

$$M = \frac{\sum_i q_i[(y_i - y_b)\cos\phi - (x_i - x_b)\sin\phi]^2}{\sum_i q_i}$$

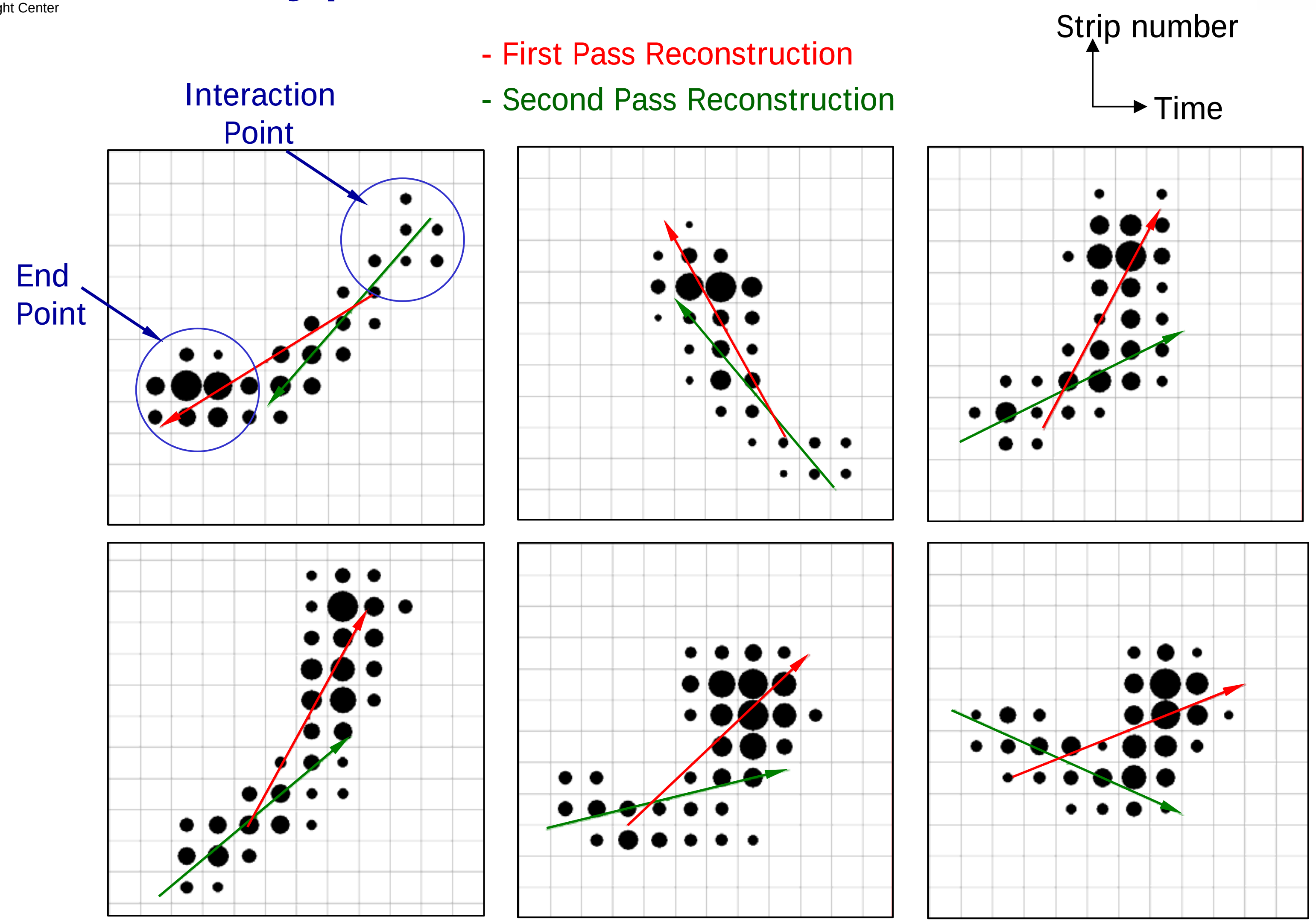
$$x_b = \frac{\sum_i q_i x_i}{\sum_i q_i}, \quad y_b = \frac{\sum_i q_i y_i}{\sum_i q_i}$$

- Second stage: same as first, but including only those pixels on the low-density side of the barycenter



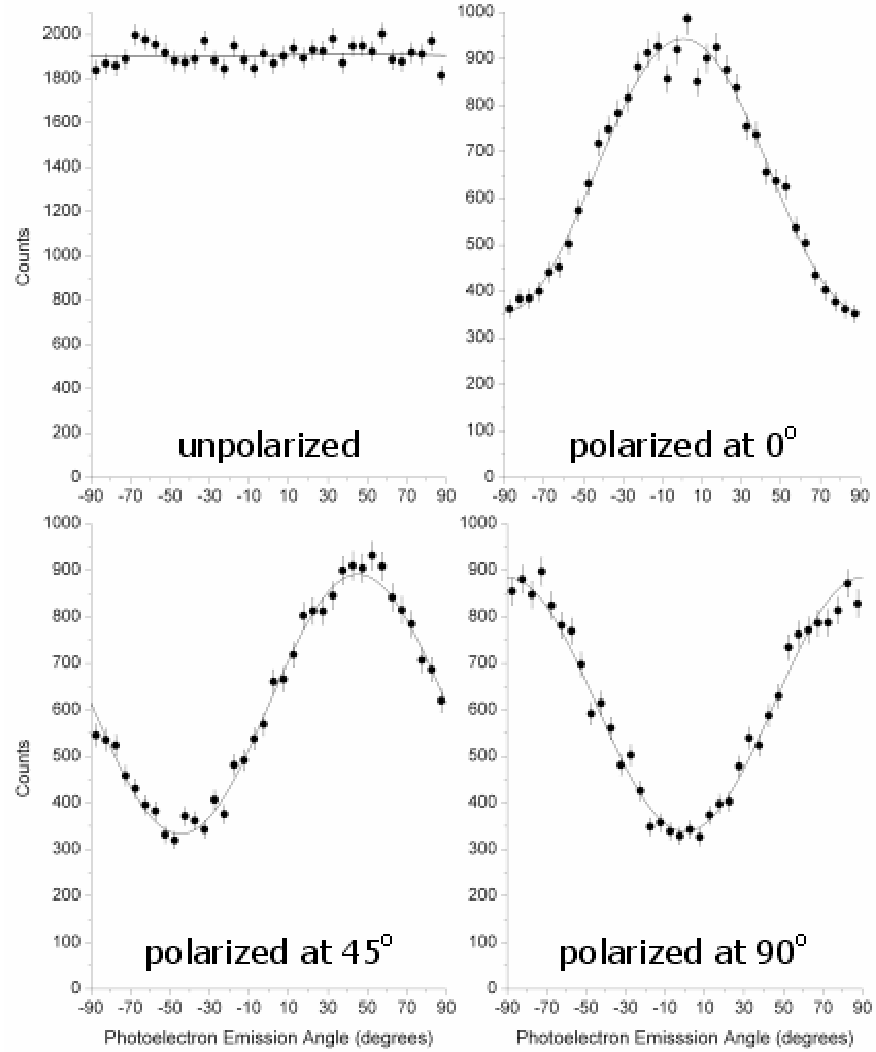
The two-stage angle reconstruction of a 6 keV X-ray. The red line shows the first-stage reconstructed track angle using the entire track. The green second-stage estimate is significantly more accurate.

Typical Reconstructed Events



Analysis and Results

- Histograms of reconstructed angles fit to expected functional form: $N(\phi) = A + B\cos^2(\phi - \phi_0)$ where ϕ_0 is the polarization phase
- The modulation is defined as: $\mu = (N_{max} - N_{min})/(N_{max} + N_{min})$
- Results:
  - It's a polarimeter
  - Uniform response
  - No false modulation



Polarization Phase	Measured Parameters		
	Modulation (%)	Phase (degrees)	χ_ν^2
unpolarized	0.49 ± 0.54	44.6 ± 28.7	1.2
0°	45.0 ± 1.1	0.3 ± 0.6	1.1
45°	45.3 ± 1.1	45.2 ± 0.6	1.0
90°	44.7 ± 1.1	-89.9 ± 0.6	1.4

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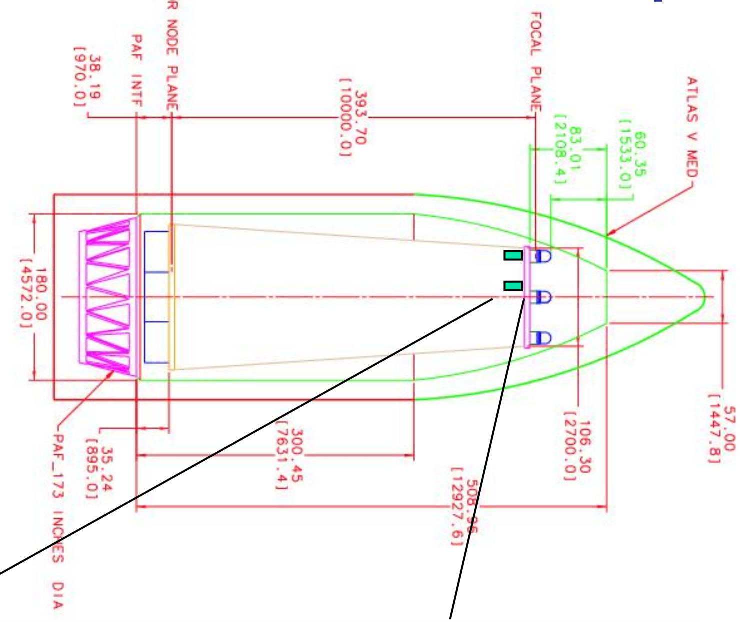
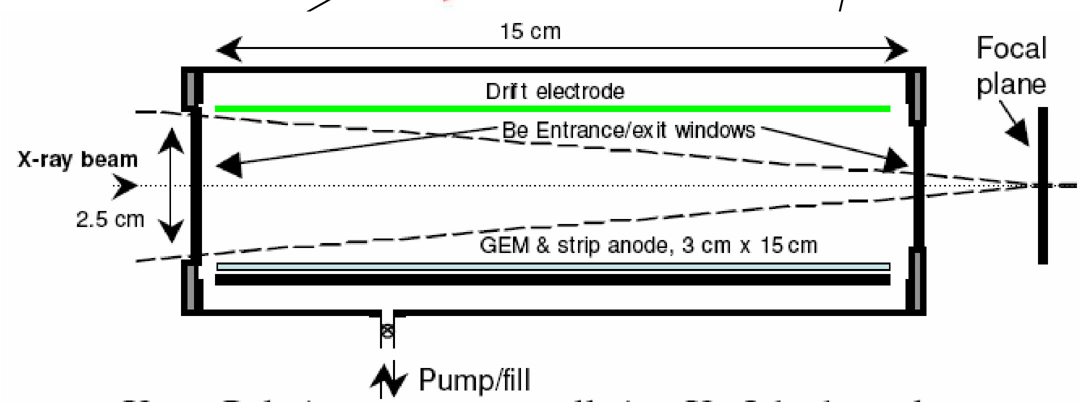
SEP Photoelectric polarimeter concept

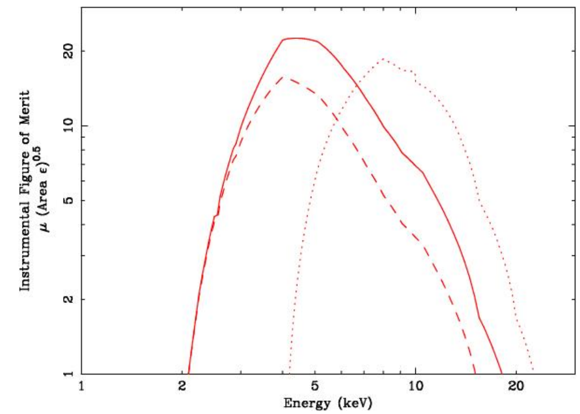
Each phototelectric polarimeter has a sealed gas filled counter, 2.5 x 2.5 x 15 cm^3 active volume, filled with Ne/DME mixture, which is commanded into (or out of) the optical path. Reference polarimeter has two independent units with orthogonal projections onto the sky

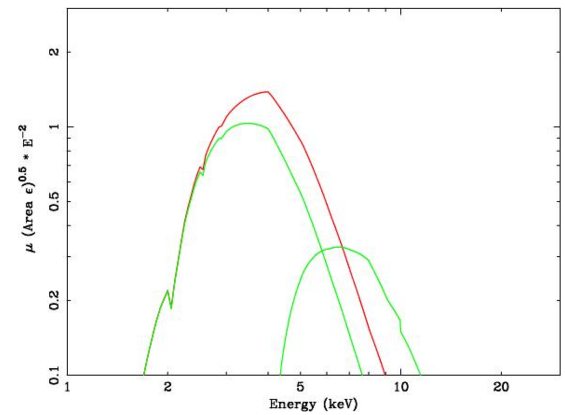




SEP Capabilities

- Polarimetry
  - $\mu \sim 0.5$
  - $\varepsilon \sim 1$
- Timing
  - μs time resolution
- Spectroscopy
  - $\Delta E/E \sim 0.18$ @ 6 keV
  - Band from 2 - 20 keV
- Imaging
  - None





Solid red line gives figure of merit for reference SEP. Dual chambered (dual gas) system could extend sensitivity to higher energies

System Impacts

Number of telescopes affected	2	polarimeter commanded in or out
Polarimeter module mass	2 x 2 kg	polarimeter plus control electronics
Mechanisms mass	2 x 5 kg	insertion, rotation, and shutter mechanism
Polarimeter operating power	2 x 20 W	Includes regulation, based on lab performance. Rotation mechanism not included
Number of Mechanisms / unit	3	insertion mechanism (filter wheel?) radioactive source shutter detector rotation
Data rate - Crab	200 kByte/s	rate for 2 polarimeters, 264 bits per event after compression; "arbitrary" reduction possible
- typical	2 kByte/s	
Contamination		risks from catastrophic window failure

Polarimetry figures of merit

- Minimum Detectable Polarization

  (MDP) ~ $(a/\mu R_s)\ (R_s + R_B)^{0.5}\ T^{-0.5}$
  - $a = 4.29$ (99% confidence)
  - $0 < \mu < 1$; μ is modulation factor
  - If $R_B << R_S$ MDP ~ $(a/\mu)\ (1/R_S T)^{0.5}$
  - Detector figure of merit ~ $\mu\varepsilon^{0.5}$
- Sensitivity may be limited by statistics or false modulation

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Control of False Modulation

- Rotation (detector or observatory) is a powerful way to suppress false modulation as all sky angles are measured at all detector angles
- For historical scattering polarimeters, rotation also induces false modulation due to misalignment of pointing and rotation axes
- TPC eliminates rotation introduced modulation,
- But measures image coordinates in fundamentally different ways
  - Careful calibration of drift velocity is desirable

Functional Schematic

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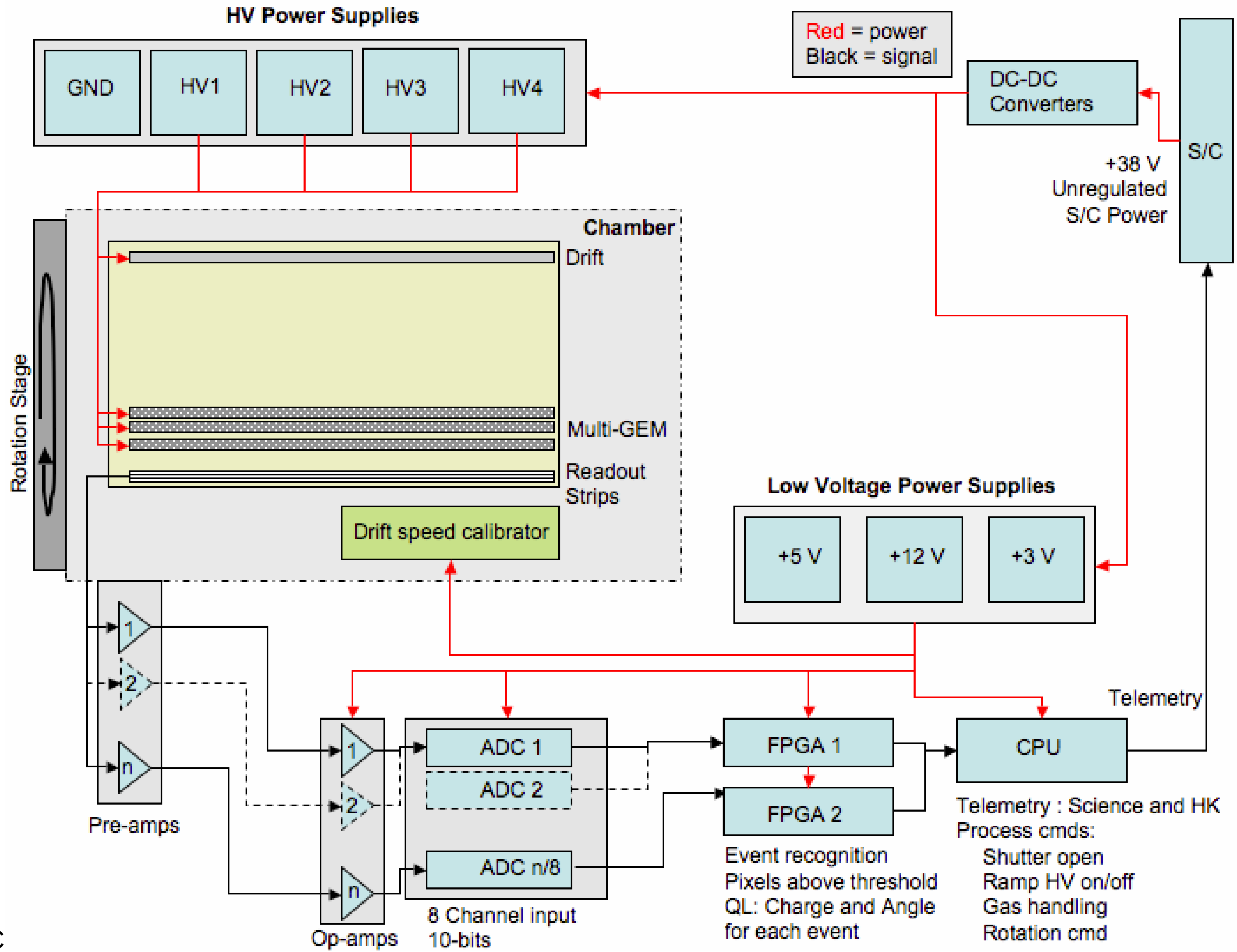
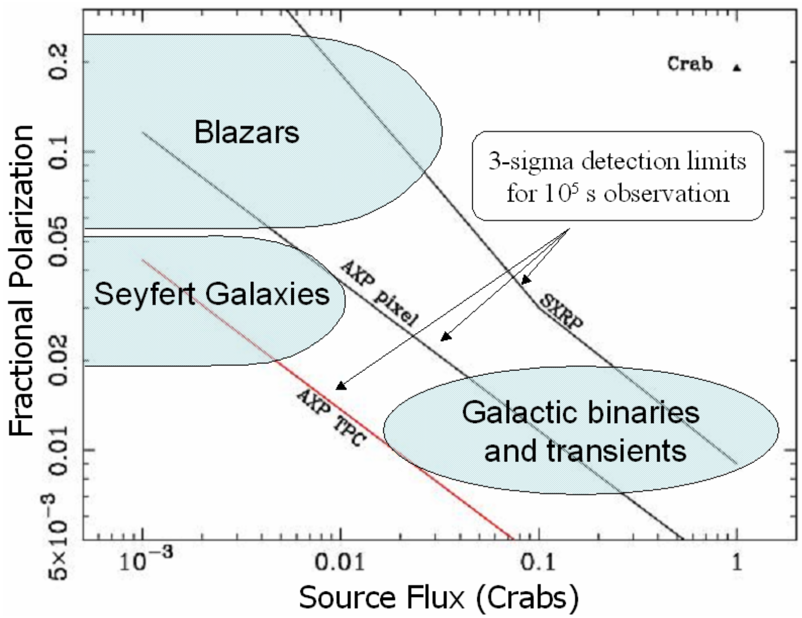


Power Budget

Operating Power

component	power (mW)	number	efficiency	total (W)
pre and post amp	100	32		3.2
ADC (8 ch input)	500	4		2.0
FPGA	550	2		1.1
master	2000	1		2.0
sub-total				8.3
LV power supply			0.75	
LV total				11.07
HV supplies	1000	4		4.0
DC-DC converter			0.75	
Total				**20.1**


Crab
Blazars
3-sigma detection limits
for 10^5 s observation
Seyfert Galaxies
AXP pixel
SXRP
AXP TPC
Galactic binaries
and transients
Fractional Polarization
5×10^{-3}
0.01
0.02
0.05
0.1
0.2
10^{-3}
0.01
0.1
1
Source Flux (Crabs)